

## X-ray sources in globular clusters

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**Abstract.** The twelve bright ( $L_x > 10^{36}$  erg s $^{-1}$ ) X-ray sources in the globular clusters have lower luminosities than the brightest sources in the bulge of our galaxy. The dim ( $L_x < 10^{35}$  erg s $^{-1}$ ) X-ray sources in globular clusters reach higher luminosities than the cataclysmic variables in the disk of our galaxy. The first difference is a statistical fluke, as comparison with M 31 indicates. The second difference is explained because the brightest of the dim sources are not cataclysmic variables, but soft X-ray transients in quiescence. This article describes the BeppoSAX, ROSAT and first Chandra observations leading to these conclusions.

### 1. Introduction

In the 1970s the first maps of the X-ray sky showed that the apparently brighter sources are concentrated towards the plane of the galaxy, and in this plane towards the galactic center (Figure 1). This indicates that these sources belong, in majority, to our galaxy, and that they have distances large enough that the galactic structure is evident, i.e.  $\sim 8.5$  kpc. Most are binaries in which a neutron star or black hole accretes matter from a companion star. The mass of the donor star is the criterium to discriminate high-mass (donor mass  $\gtrsim 10 M_\odot$ ) and low-mass ( $\lesssim 2 M_\odot$ ) X-ray binaries (as reviewed by e.g. Verbunt 1993). The luminosities of the low-mass X-ray binaries ranges up to  $L_x \simeq 10^{38}$  erg s $^{-1}$ . Many are bright permanently, but transient sources only during outbursts which last a month, typically, and which repeat on time scales ranging from six months to many decades (e.g. Chen et al. 1997).

Whereas globular clusters contain only of order 0.1% of the stars in our galaxy, the current count is that they harbour 12 of the  $\sim 100$  permanently or transiently bright low-mass X-ray sources. The overabundance of bright X-ray sources in globular clusters is caused by close encounters between neutron stars and main-sequence or (sub)giant stars leading to the formation of low-mass X-ray binaries (reviewed by Hut et al. 1992). A tidal capture occurs when a neutron star passes close enough to another star to raise a tidal bulge on it; the energy of the bulge is taken from the relative orbit of the stars, which as a consequence becomes bound. The efficiency of tidal capture is the subject of debate, as rapid dissipation of the energy in the bulge may destroy the star, leaving the neutron star alone again, or with a disk around it. An exchange encounter is the process in which a neutron star takes the place of one of the two members of a binary,

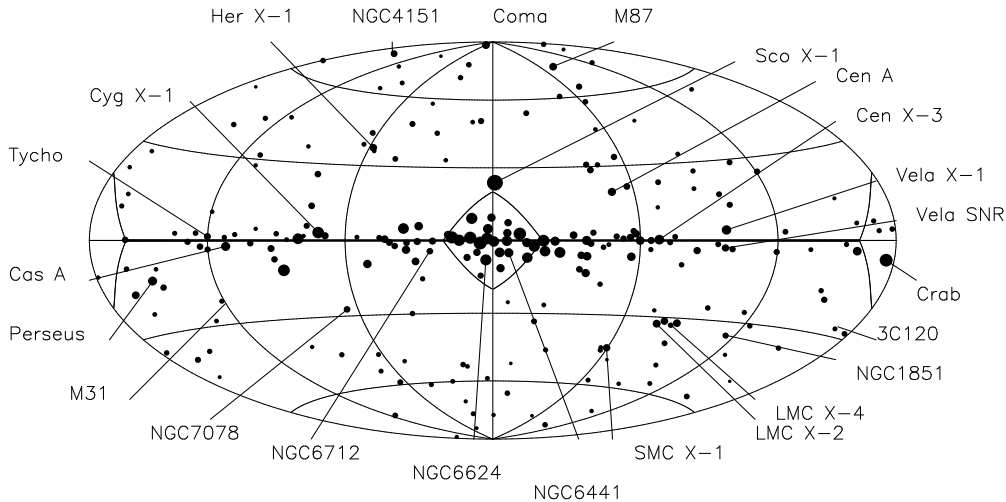


Figure 1. The brighter X-ray sources of the sky (from the 3rd Ariel V catalogue, McHardy et al. 1981) are concentrated towards the galactic plane, and in this towards the galactic center. Thus a pointing at the galactic center with the BeppoSAX Wide Field Cameras, with a field of view indicated by the deformed lozenge in the middle, observes half of the bright low-mass X-ray binaries simultaneously, including many globular cluster sources. Some globular clusters with bright X-ray sources are indicated with their NGC numbers.

by ejecting it. The efficiency of exchange encounters depends on the number and period distribution of binaries in the cluster cores.

In addition to the bright sources, globular clusters also contain dim sources, with X-ray luminosities  $L_x \lesssim 10^{35} \text{ erg s}^{-1}$ , as discovered with the Einstein satellite (Hertz & Grindlay 1983). The nature of these sources is less clear.

In this article I first explain how Jan van Paradijs awoke my observational interest in cluster sources, and then review the new results on the bright sources, mainly due to BeppoSAX; and the ROSAT and first Chandra results on the dim sources.

## 2. Jan van Paradijs gets me involved

In July 1983, as a postdoc in Cambridge (U.K.), I received a letter from Jan van Paradijs in which he points out that the bright X-ray sources in globular clusters do not reach the luminosities of their counterparts near the galactic center (see Figure 2); he asked me whether it could be a consequence of lower mass donors in globular clusters, due to a different formation mechanism in clusters (via close encounters) than in the disk (via binary evolution). While thinking about this, we ran into two puzzling facts (Verbunt et al. 1984).

First, the X-ray sources in globular clusters in M31 *are* as bright as the galactic bulge sources. This defeated any explanation we could think of for the

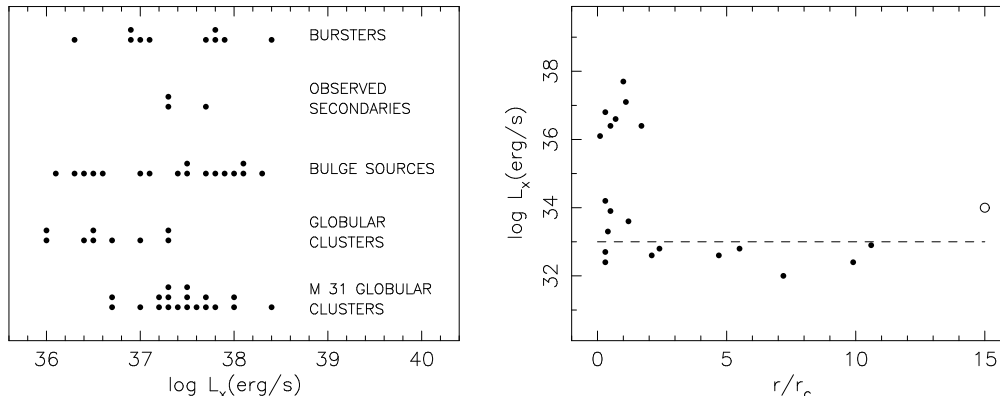


Figure 2. Reproduction of Figs.1 (left) and 4 (right) of Verbunt et al. (1984). The left figure showed that the globular cluster sources in our galaxy do not reach the brighter luminosities measured for sources in the galactic disk (with distances from location near the galactic center, from an optical companion, and from bursts), but that those in globular clusters in M31 do reach these brightnesses. The right figure shows that the dim ( $< 10^{35} \text{ erg s}^{-1}$ ) globular cluster sources that are brighter than the brightest cataclysmic variables in the galactic disk (i.e. above the dashed line) are within 2 core radii from the cluster center, just as the bright cluster sources. The brightest out-of-core source (o) is a marginal Einstein source outside NGC 5824, not detected in later, more sensitive observations with ROSAT (Verbunt 2001). Note that both figures would look different with current data.

low luminosities of the cluster sources in our galaxy, and I have since come to think that these low luminosities are a statistical fluke.

Secondly, the dim sources had been suggested by their discoverers, Hertz & Grindlay, to be cataclysmic variables; however, they are *brighter* in X-rays than the cataclysmic variables in the galactic disk. Could they be neutron stars accreting at a low rate, i.e. soft X-ray transients in their quiescent state? If so, they should reside near the cores, and so we plotted the X-ray luminosities of the globular cluster sources as a function of distance to the cluster center, to find that the dim sources with  $L_x \gtrsim 10^{33} \text{ erg s}^{-1}$  do indeed lie inside two core radii, just as the bright sources (Fig. 2). We thus proposed that the sources with  $L_x \gtrsim 10^{33} \text{ erg s}^{-1}$  are transients in quiescence, and those less luminous a mix of transients and cataclysmic variables. (Later it would appear that the Einstein sources outside the core are not related to globular clusters – see Sect. 4.)

At the time of our proposal no transient had ever been detected in X-rays in quiescence. To amend this, we obtained observations with EXOSAT of two transients, Aql X-1 and Cen X-4. We detected Cen X-4, and its luminosity was exactly in the range of brightest of the dim globular cluster sources (Van Paradijs et al. 1987). This convinced us of the correctness of our proposal.

### 3. New results on bright cluster sources

The globular clusters are concentrated towards the galactic center, and the  $40^\circ \times 40^\circ$  field of view of the BeppoSAX Wide Field Cameras can observe a large fraction of them simultaneously (Fig. 1), allowing the discovery of rare events.

In a campaign of the galactic center, X-ray bursts – thermonuclear flashes on the surface of a neutron star – have been discovered in the bright sources of NGC 6652 and NGC 6440 (In 't Zand et al. 1998, 1999). These results bring the total of bright globular cluster sources from which a burst has been detected to 11; leaving the source in Terzan 6 as the only one remaining in which no thermonuclear burst has been unambiguously detected. This means that 11 of the 12 currently known permanent or transient bright sources in globular clusters, and possibly all 12 of them, harbour a neutron star. (It may be remarked that one of the other elusive burst sources, the one in M 15, was caught by Van Paradijs et al. 1990; I thank Phil Charles for reminding me of this.)

A possible explanation for the absence of X-ray binaries with a black hole in globular clusters has been provided by Portegies Zwart & McMillan (2000; see also Kulkarni et al. 1993). Once the more massive stars in a globular cluster have evolved, the black holes – if they have masses similar to the black holes in the galactic disk, i.e. of about  $7 M_\odot$  (Bailyn et al. 1998) – are the most massive objects in the cluster by a large margin, the next most massive stars being the  $1.4 M_\odot$  neutron stars. As a result the black holes sink to the deepest part of the potential well, where they form binaries by exchanging into primordial binaries. Interactions between binary and single black holes lead to reaction velocities larger than the escape velocity of the cluster, and effectively clear the globular cluster of black holes.

Another result of BeppoSAX was the discovery of faint, short-lived X-ray transients, e.g. in NGC 6440 (in 't Zand et al. 1999). This raises the question how many of such transients are missed by other satellites, that do not have the spatial resolution to overcome source confusion and discover such outbursts in the vicinity of the galactic center. The outburst in NGC 6440 of 1998 reached a maximum of only  $6 \cdot 10^{36} \text{ erg s}^{-1}$ , and had an exponential decay time of about 5 d; very different from the 1972/1973 outburst, which stayed at a luminosity of  $3 \cdot 10^{37} \text{ erg s}^{-1}$  during more than a month (Markert et al. 1975, Forman et al. 1975). This raises the question whether NGC 6440 harbours more than one transient; or alternatively how one source can show such extremely different outbursts.

Finally, with BeppoSAX eclipses were discovered in the source in Terzan 6, and on the basis of these the orbital period was determined to be 12.36 h (in 't Zand et al. 2000). Of the five orbital periods now known for globular cluster sources, only one has a period in the range compatible with a main-sequence donor, viz. the source in NGC 6441 with a period of about 5.7 h (Sansom et al. 1993). Two have periods suggesting a subgiant donor, viz. 12.36 and 17.1 h; and two periods suggesting a white-dwarf donor, at 11.4 and 20.6 m (Ilovaisky et al. 1993, Stella et al. 1987, Homer et al. 1996). Van Paradijs & McClintock (1994) found an observational relation between the X-ray luminosity, the orbital period, and the visual brightness of low-mass X-ray binaries. They also provided a heuristic argument to explain it: a large orbital period allows a large disk, which when irradiated by a high X-ray luminosity will be a bright source of

optical radiation. Conversely, if the optical counterpart of a bright X-ray source is faint in the optical, the orbital period must be small, and this reasoning is used by Deutsch et al. (2000) and Homer et al. (2001) to argue that the donors of the sources in NGC 1851 and NGC 6652 also are white dwarfs. The prevalence of ultra-short period systems, and thus presumably of white-dwarf donors among the globular cluster X-ray sources underscores the difference in formation mechanism of globular cluster X-ray sources and of low-mass X-ray binaries in the galactic disk. In particular, it indicates the importance in clusters of direct collisions between single neutron stars and sub-giants in the formation of ultra-compact binaries (Verbunt 1987).

#### 4. The dim sources: ROSAT

The debate on the nature of the dim sources widened as ROSAT observations of sources in the galactic disk showed that recycled neutron stars and RS CVn binaries may have luminosities comparable to the luminosities of the faintest dim sources. ROSAT observations of cataclysmic variables and soft X-ray transients in quiescence confirmed that only the transients reach the luminosities of the brightest dim sources (Figure 3). ROSAT also showed that soft X-ray transients in quiescence show a soft spectrum ( $kT_{\text{bb}} \lesssim 0.4 \text{ keV}$  for a black body fit; Verbunt et al. 1994), to which ASCA added a hard power-law tail (Asai et al. 1998). In an important paper, Brown et al. (1998) showed that the quiescent X-ray spectrum of soft X-ray transients is quiescence is dominated by thermal emission from the neutron star, and that fits of neutron-star atmosphere models leads to realistic radii for the neutron stars. The few dim cluster sources for which ROSAT could provide spectral information appear to be equally soft (Verbunt 2001).

It further became clear that the dim sources found with Einstein outside the cluster cores (and shown in Fig. 2) are fore- or background sources (Margon & Bolte 1987, Cool et al. 1995), or nonexistent (Verbunt 2001)! However, ROSAT detected new out-of-the core sources which according to a simple statistical argument in majority *are* related to the globular clusters (Verbunt 2001); this includes a dwarf nova in the outskirts of NGC 5904 (Hakala et al. 1997).

The ROSAT HRI managed to resolve the dim sources in the cores of 47 Tuc, NGC 6397 and NGC 6752 in 5, 4 or 5, and 4 sources, respectively; in  $\omega$  Cen three sources were detected in the core (Verbunt & Hasinger 1998, Verbunt & Johnston 2000). Second, the more accurate ROSAT positions spurred HST searches for optical counterparts. Several blue variables – possibly cataclysmic variables – in the core of 47 Tuc were proposed as counterparts to the X-ray sources (Paresce et al. 1992, Paresce & de Marchi 1994, Shara et al. 1996); but chance coincidence could not be excluded (Verbunt & Hasinger 1998). Similarly, the proposed identifications of stars with  $H\alpha$  emission in NGC 6397 (Grindlay et al. 1995, Edmonds et al. 1999),  $\omega$  Cen (Carson et al. 2000), and of variables with periods of 5.1 and 3.7 h in NGC 6752 (Bailyn et al. 1996), with dim X-ray sources in these clusters are plausible, but due to the uncertain positions not certain. In my view it has been too easily assumed that these sources are cataclysmic variables: variability and  $H\alpha$  emission are also properties of X-ray transients in quiescence. In any case, none of the proposed identifications concern the brighter dim sources proposed to be quiescent soft X-ray transients by Verbunt

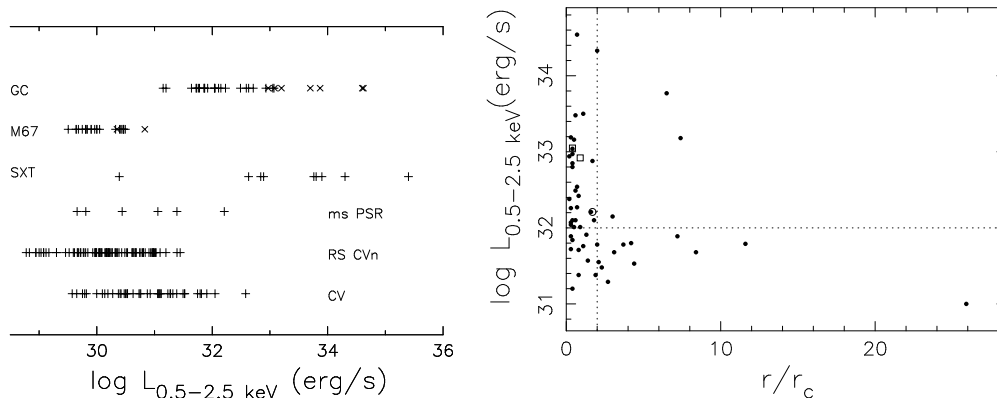


Figure 3. Left: The X-ray luminosities as determined with ROSAT of the dim sources in globular clusters compared to those of various types of sources in the galactic disk, from top to bottom: sources in the old open clusters M 67 and NGC 188, soft X-ray transients, recycled millisecond pulsars, RS CVn binaries, and cataclysmic variables. For each category, the lower limit is set by the detection limit. The luminosities of the brightest dim sources are matched by the soft X-ray transients only (from Verbunt 1996). Right: X-ray luminosities of globular cluster sources as a function of their distance to the cluster center, in units of the core radius, based on ROSAT data (Verbunt (2001)). The proposed quiescent soft X-ray transient in  $\omega$  Cen is indicated  $\circ$ , those in 47 Tuc  $\square$ . The horizontal dotted line indicates the level of the brightest cataclysmic variables in the galactic disk, which due to the narrower bandpass is lower than the (Einstein) level of Fig. 2.

et al. (1984). The one secure identification of a dim core source before Chandra is that based on the periodicity of the recycled pulsar in M 28 (not by Danner et al. 1994, who unwittingly analyzed background photons, but by Saito et al. 1997; see discussion in Verbunt 2001). The luminosity function of the core sources was analyzed by Johnston & Verbunt (1996), who found that the total luminosity of most globular clusters is dominated by a few relatively bright dim sources, rather than large numbers of very dim sources.

Finally, a comparison showed that most globular cluster have a lower X-ray luminosity to mass ratio than the old open cluster M 67 (observed by Belloni et al. 1998), which indicates that sources of the (ill-understood) types responsible for most X-rays in M 67 are not present in globular clusters (Verbunt 2001).

## 5. The first Chandra results on dim sources

The first images of globular clusters obtained with Chandra confirm its superior angular resolution as compared to the already impressive ROSAT HRI. Chandra resolves the central source of NGC 6752 into nine sources (Pooley et al. 2001; see Fig. 4). Five of these sources have X-ray fluxes and colours suggestive of cataclysmic variables. Work on the optical identification is in progress, and has

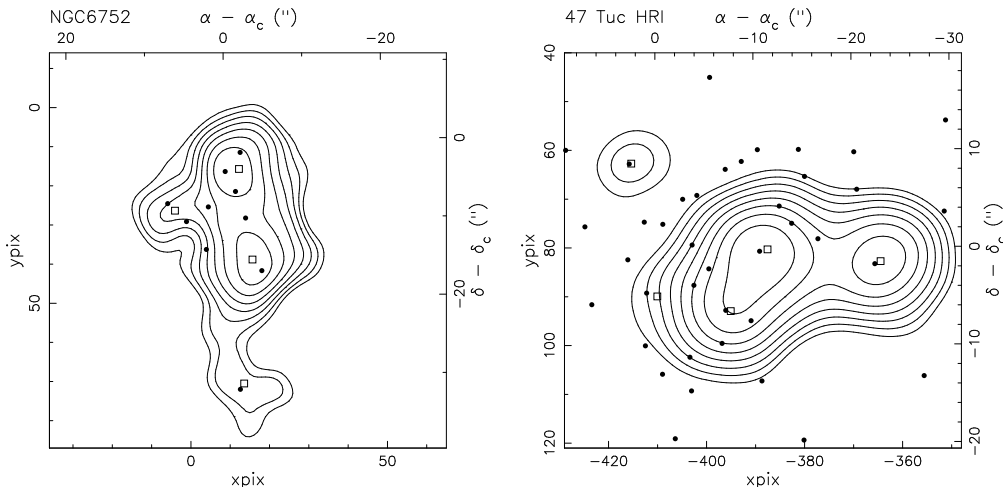


Figure 4. The X-ray positions of sources in cluster cores detected with Chandra ( $\bullet$ ) superposed on ROSAT HRI contours and positions ( $\square$ ). Left NGC 6752 (Pooley et al. 2001; Verbunt & Johnston 2000); right 47 Tuc (Grindlay et al. 2001; Verbunt & Hasinger 1998).

found evidence for  $H\alpha$  emission for the candidate counterparts of these sources (Homer et al. in preparation). However, the flux distribution of the brightest X-ray source is best fitted with a power law. The two optical variables discovered by Bailyn et al. (see previous section) are both detected as X-ray sources.

The globular cluster  $\omega$  Cen has a larger core, and Chandra doesn't add to the three sources already found with ROSAT in this core. However, the Chandra observation does provide spectral information, and this has been used by Rutledge et al. (2001) to show that the brightest source in  $\omega$  Cen, outside the cluster core but within the half-mass radius, has a spectrum similar to those of soft X-ray transients in the galactic disk. The spectral fit gives a radius of about 10 km at the distance of  $\omega$  Cen, and confirms the membership of this source to the cluster.

The most spectacular Chandra observation of a globular cluster is that of 47 Tuc, in which a large number of sources is detected (Grindlay et al. 2001). On the basis of their soft X-ray colours, the brightest two sources (X5 and X7 from the ROSAT HRI observations; Verbunt & Hasinger 1998) are argued to be soft X-ray transients in quiescence – a nice confirmation of the suggestion discussed in Sect. 2. Thirteen sources are probably cataclysmic variables, on the basis of their hard X-ray colours. Fifteen recycled radio pulsars have been found with the source detection algorithm; the  $1''$  accuracy of the Chandra positions allows the detections of two of them on the basis of *three* photons and *one* photon, respectively! Six sources can be optically identified with main-sequence binaries.

In Fig. 4 I plot the positions of the Chandra sources in 47 Tuc on top of the ROSAT HRI image. Comparison of the positions of 8 HRI sources and their Chandra counterparts, shows that the overall shift required to bring the ROSAT positions into agreement with the Chandra positions is  $-0''.7, -0''.5$  in

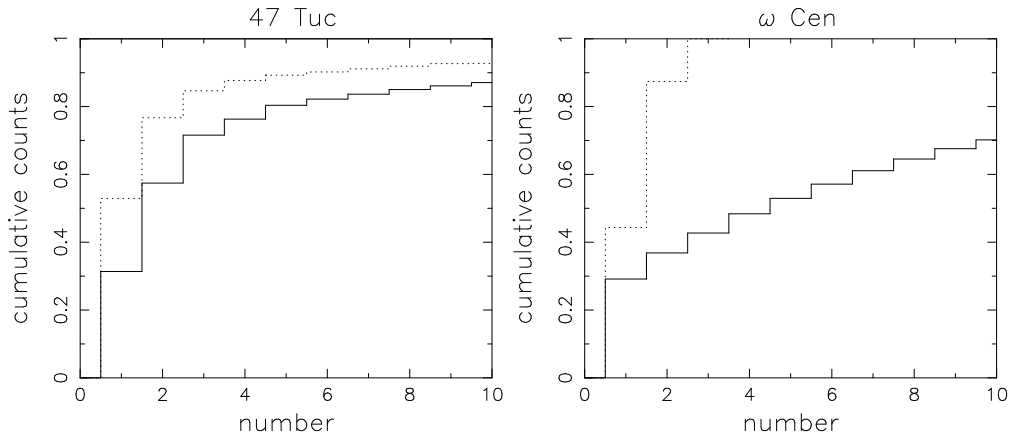


Figure 5. Cumulative fraction of total X-ray luminosity partaken by sources detected with Chandra in 47 Tuc (left) and in  $\omega$  Cen. The full line is for all the sources near the cluster, including background sources; the dotted line for the core only.

right ascension and declination respectively; after application of this shift, all 8 sources coincide within the errors with the Chandra sources. Thus the positional accuracy claimed by Verbunt & Hasinger is confirmed. In Fig. 5 I plot the cumulative X-ray flux of the Chandra sources, starting with the brightest one. This plot confirms the ROSAT result that the total luminosity of 47 Tuc is dominated by the few brightest sources. For example, the fifteen detected recycled pulsars together emit less than 4% of the flux of the brightest source alone.

The measured period derivatives of the recycled pulsars are dominated by gravitational acceleration in the cluster (Freire et al. 2001). The low X-ray luminosities of these pulsars provide an indirect estimate to their intrinsic period derivatives, and thus to their age, if we use the empirical relation found by Verbunt et al. (1996) that  $L_x \simeq 10^{-3} L_{sd}$ , where  $L_{sd} = 4\pi^2 I \dot{P} / P^3$  is the spindown luminosity. If we take the average period of the recycled pulsars in 47 Tuc as  $\sim 4$  ms, and the average X-ray luminosity  $L_x \sim 3 \cdot 10^{30} \text{ erg s}^{-1}$ , the characteristic age  $\tau_c \equiv P / (2\dot{P})$  is comparable to the age of the cluster. This suggests that most currently detected recycled pulsars were formed soon after the formation of 47 Tuc.

## 6. Conclusions and prospects

The 12 permanently or transient bright X-ray sources in the globular clusters of our galaxy are neutron stars. The dearth of high-luminosity ( $\gtrsim 10^{37} \text{ erg s}^{-1}$ , say) sources among them appears to be a fluke of small-number statistics.

Among the dim sources, all types proposed as possible dim sources, i.e. soft X-ray transients in quiescence, cataclysmic variables, recycled pulsars, and chromospherically active close binaries are now detected in Chandra observations. For more secure identification of  $H\alpha$ -emission systems with cataclysmic



variables, it would be useful if a compilation of  $H\alpha$  line fluxes of soft X-ray transients *in quiescence* were available. The total core luminosity of a globular cluster is dominated by a few bright sources, rather than large number of dim sources. Globular cluster cores and *a fortiori* globular clusters as a whole emit less X-rays per unit mass than the old open cluster M 67.

Chandra has opened a golden age for the study of X-ray sources in globular clusters. Together with HST, this will for the first time provide us with good statistics of the numbers of binaries in the cores of globular clusters, an important ingredient in the study of cluster evolution.

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